Development of A High Field Magnet for Neutrino Factory Storage Rings

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LDRD Project # 01-79

PURPOSE:

The purpose of this LDRD was to develop a dipole magnet design that allows a compact Neutrino Factory Storage Ring. The magnet design minimizes the energy deposition on the superconducting coils due to showers initiated by muon decay products. A compact storage ring minimizes the environment impact by keeping the entire machine above the ground water table at BNL. The applications of such magnet designs go well beyond that of Neutrino Factory. In particular, they are applicable in the interaction region magnets of next generation hadron colliders.

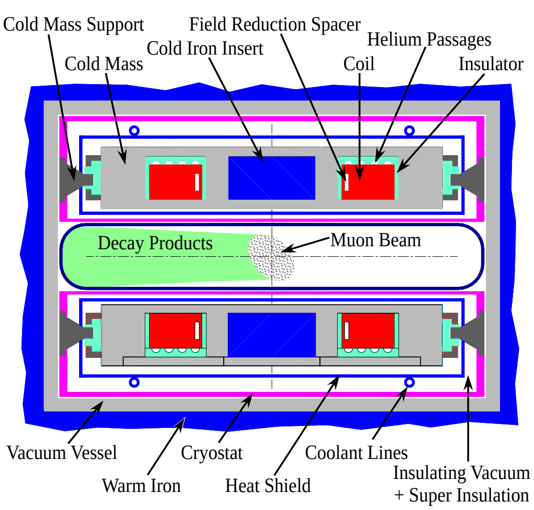

Figure 1: Cross section, with main features labeled, of neutrino factory muon storage ring magnet that avoids decay particles directly hitting superconducting coils.

APPROACH:

A racetrack coil magnet design with open midplane gap keeps decay particles away from directly hitting superconducting coils. This eliminates the need for a "tungsten liner" which is expensive and occupies a critical real estate in high field magnets. The flat racetrack coils have a large bend radius in the ends. A large bend radius allows the use of "react and wind" magnet technology that is suitable for Nb_3Sn and High Temperature Superconductors.

TECHNICAL PROGRESS AND RESULTS:

A dipole magnet design for the proposed Neutrino Factory Storage Ring has been developed. The dipole operating field is 6.93 T and the design quench field is over 8 T for an operating field margin of over 15%. The cross-section of this design is shown in Fig. 1.

The maximum field on the conductor at quench is significantly higher than the central field and excludes using NbTi at 4.2 K. The coils therefore are made from brittle Nb_3Sn superconductor. A large bend radius in the ends and a simple pancake coil (racetrack) geometry allows the use of "react and wind" magnet technology.

The superconducting collared coils inside a cryostat clear the magnet midplane region where most of the decay energy goes. A warm iron yoke structure around the coils then allows heat generated by decay particles to be removed efficiently at a higher temperature.

The superconducting coils are contained in cold masses surrounded by a heat shield and cryostat. Large vertical forces, that could be either attractive or repulsive, depending on the configuration, are contained with the help of support keys mounted to the yoke. The overall magnet structure is designed to minimize the heat leak through the support keys while containing the large Lorentz forces.

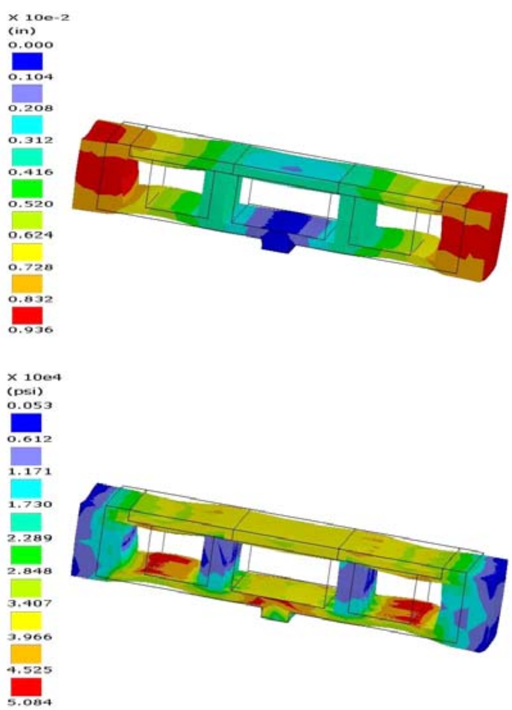

Figure 2: Final Element Analysis shows that the optimized coil support structure has deflections below 10 mil (0.25 mm) and stresses below 50 kpsi.

The finite element analysis codes were used to minimize the deflections and stresses on superconducting coils and on the support structure. The results of the optimized model of coil support structure are shown in Fig. 2. The analysis shows that the deflections are less than 10 mil (0.25 mm) and stresses are less than 50 kpsi.

The design of support keys provided another challenge. It must balance between the conflicting requirements of low heat leak and low deflections. The material of the support keys and cryogenic structure was chosen carefully. An optimum support key design was developed where the deflections were less than 5 mil (0.125 mm) and stresses were less than 80 kpsi. The estimated heat load is about 7 Watt. The results of finite element analysis of this structure of support keys are shown in Fig. 3.

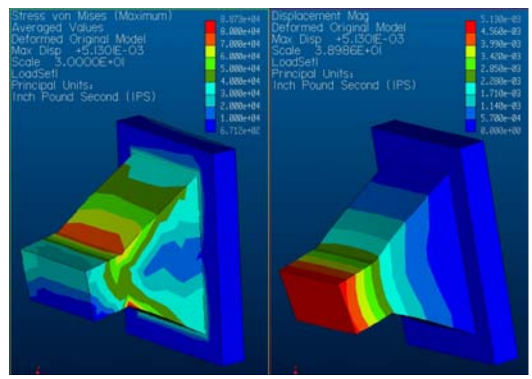

Figure 3: Final Element Analysis shows that the optimized key structure has deflections below 5 mil (0.125 mm) and stresses below 80 kpsi.

To maintain field strength, we minimize the vertical distance between the coils and the beam cavity. The cryostat wall thickness is minimized on the side near the beam tube. The beam tube is warm and its thickness is as small as possible. Surrounding both cold masses and the beam cavity is an outer vacuum vessel that eliminates differential pressure on the cryostats and beam tubes and prevents them from collapsing under vacuum.

This project does not involve animal vertebrates and human subjects.

SPECIFIC ACCOMPLISHMENT:

We have developed a new magnet design that allows compact Neutrino Factory Storage Rings to be constructed at BNL site. It was observed, during the course of this LDRD, that a skew quadrupole lattice avoids the direct hit of a large number of decay particles on quadrupole magnets as well. A lattice with skew quadrupole has been developed and presented in the following paper:

B. Parker, Skew-Quadrupole Focusing Lattices and Their Applications, 2001 Particle Accelerator Conference, Chicago, 18-22 June, 2001.

In addition, a novel magnet system designed has been developed where all focusing is provided in the ends (see Fig. 4 and Fig. 5). This concept has been presented in the following paper:

B. Parker, M. Anerella, A. Ghosh, R. Gupta, M. Harrison, J. Schmalzle, J. Sondericker, and E. Willen, Magnets for a Muon Storage Ring, 2001 Particle Accelerator Conference, Chicago, 18-22 June, 2001.

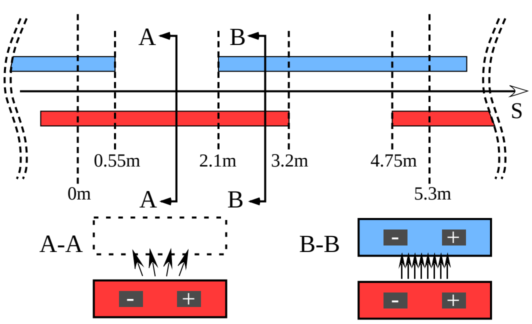

Figure 4: Design-A coil and cryostat layout schematic. Regions with no coil overlap, A-A, have half strength dipole field + skew quadrupole field. Full dipole field and no skew quadrupole occurs in overlap region, B-B.

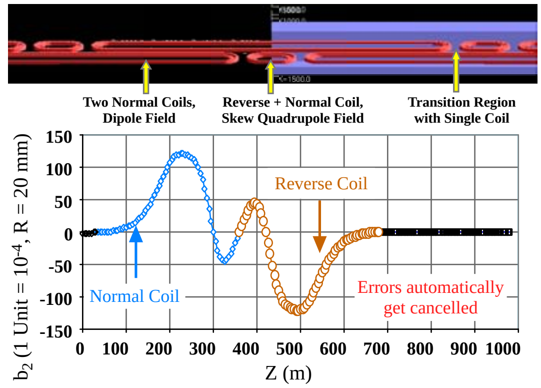

Figure 5: Design-B coil layout and an example of end harmonic cancellation. Since normal and reverse coils have same ends, their coil end field harmonics cancel.

In Fig. 4 (Design A), the coil packages are longitudinally staggered to provide focusing (F) or defocusing (D) skew quadrupole combined function magnets where there is only a single coil on the top or the bottom. A pure dipole field occurs in overlap regions. The dipole guide field in non-overlap regions is about half that in overlap regions. Thus, the structure has continuous bending and alternate gradient skew focusing. Space normally lost at coil ends and magnet interconnects is efficiently used.

Design B, employs a novel approach that is developed during the course of this LDRD. This approach introduces small coils with reverse polarity. In addition to making a skew quadrupole, these reverse coils provide an automatic cancellation of normal and skew harmonics in the end region as shown in figure 5. The magnet cross section has been designed to produce a dipole field with a field error of only about one part in 10,000. The expected field harmonic errors for the dipole section for a theoretical magnet design, in combination with previous magnet design and construction experience, are given in Table 1.

Table 1: The estimated *Design-B* dipole field errors at 20 mm reference radius, $b_0 = 10^4$. b_n and a_n are expected means of normal and skew terms, δb_n and δa_n systematic uncertainties, and $\sigma\ b_n$ and σa_n random uncertainties. $n = 2$ corresponds to a sextupole.

n	b_n	δb_n	$\sigma\ b_n$	a_n	δa_n	σa_n
1	0	0.2	0.2	0	1	2
2	-1	1	2	0	0.1	0.5
3	0	0.1	0.1	0	0.3	1
4	-1	1	1	0	0.05	0.2
5	0	0.03	0.03	0	0.1	0.5
6	-0.3	0.2	0.1	0	0.03	0.1
7	0	0.03	0.01	0	0.03	0.1
8	-0.1	0.1	0.02	0	0.03	0.1
9	0	0.03	0.01	0	0.03	0.1

This, however, still leaves an axial component of the field in the lattice.

As a part of this LDRD, the engineering designs of coil, coldmass and the magnet test setup have been developed. They are shown in Fig. 6.

The following are other significant publications related on Neutrino Factory and Muon Collider that are based on the work performed under this LDRD:

S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo ed., Feasibility Study-II of a Muon-Based Neutrino Source, BNL-52623 (2001).

N. Mokhov, C. J. Johnstone, B. Parker, Beam-Induced Energy Deposition in Muon Storage Rings, 2001 Particle Accelerator Conference, Chicago, 18-22 June, 2001.

In addition several talks are given by principle investigators at various meetings. These include Muon Collider Collaboration Meetings, Editorial Meetings on Neutrino Factory Feasibility Study, Symposium on Neutrino Factory Study II and presentations at Snowmass 2001.

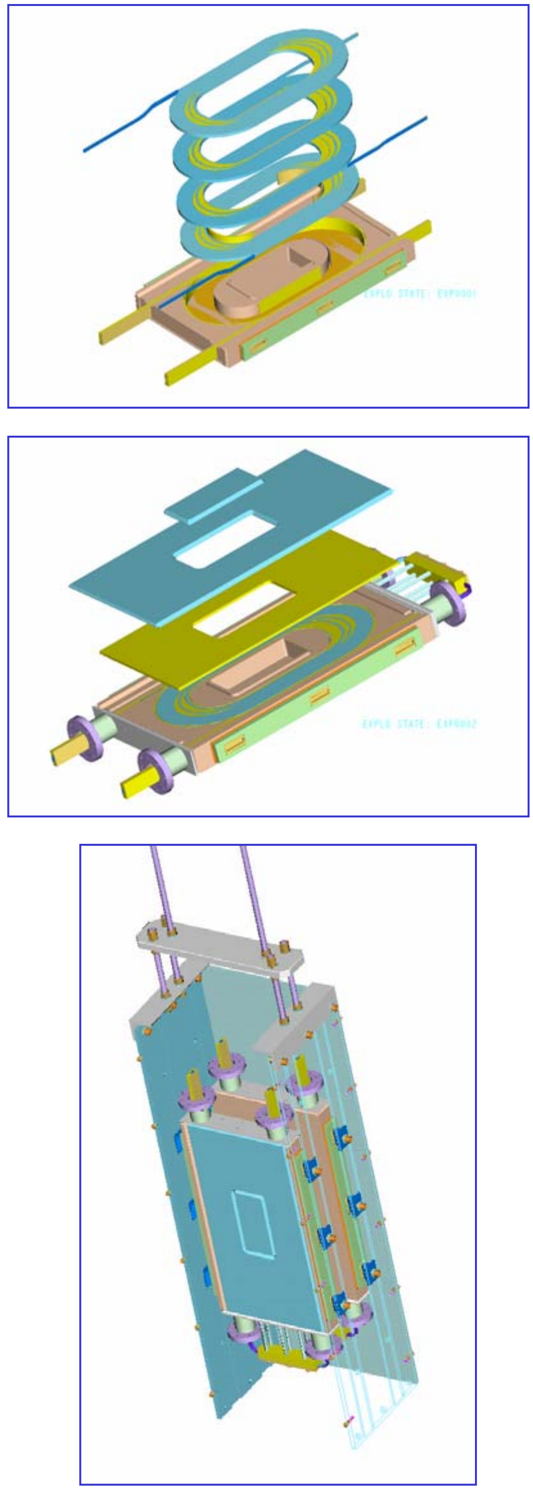

Figure 6: The engineering designs of coil, coldmass and the magnet test setup.

The R&D supported in part by this LDRD has resulted in developing a magnet design concept that is now being considered for the interaction region magnets of either future colliders or for the upgrade of present collider. In particular, this design is being considered for the LHC IR upgrade option where the beam separation dipole is placed before the quadrupole triplet. In this case the first magnet is subjected to large radiation and heat load, a situation very similar to that in Neutrino Factory Storage Ring. A layout of such lattice (developed by CERN) is shown in Fig. 7.

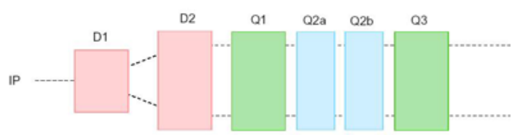

Figure 7: The dipole design concept developed here is suitable in the LHC IR Upgrade lattice proposed by CERN in the "Dipole First" option.

LDRD FUNDING:

FY 2000	$98,000.00
FY 2001	$100,000.00